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ScienceDirect

Energy Procedia 71 (2015) 69 – 77

Energy Procedia

The Fourth International Symposium on Innovative Nuclear Energy Systems, INES-4

Self-sustaining thorium-fueled reduced moderation BWR feasibility study

Jeffrey E. Seifried[a], Guanheng Zhang[a], Christopher R. Varela[a], Phillip M. Gorman[a]*, Ehud Greenspan[a], Jasmina L. Vujic[a]

[a]*Department of Nuclear Engineering, University of California Berkeley, 3115 B&AA Etcheverry Hall, Berkeley, CA, USA, 94720-1730*

Abstract

This study assesses the feasibility of a thorium-based fuel-self-sustaining Reduced moderation BWR (RBWR-Th) core. This core features a hexagonal tight-lattice fuel, high exit coolant quality, axial segregation of seed and blanket regions, and compatibility with the ABWR reactor vessel inherited from the RBWR-AC proposed by Hitachi. The RBWR-Th differs from the RBWR-AC by eliminating the internal blanket, eliminating absorbers from the axial reflectors, replacing depleted urania with thoria as the primary fertile fuel and elongating the fissile region. When the Hitachi assumptions and correlations for thermal-hydraulic analysis are used, the RBWR-Th obtains an average core discharge burnup of 61 GWd/t versus 45 GWd/t for the RBWR-AC. However, when more conservative thermal-hydraulic correlations are used, the average discharge burnup drops to 25 GWd/t. The RBWR-Th maintains negative coolant void coefficients of reactivity throughout the cycle – between -155 and -131 pcm/% – but currently does not have sufficient margin for cold shutdown. Future studies will address this shutdown margin deficit and will account for coolant pressure drop constraint.

Selection and peer-review under responsibility of the Tokyo Institute of Technology

Keywords: thorium; reduced moderation; BWR; breeder; multi-recycling; equilibrium

1. Introduction

The RBWR-Th core design is based upon the Hitachi designed RBWR-AC [1], a reduced-moderation BWR which has an axially segregated seed and blanket for fuel-self-sustaining operation within an ABWR pressure vessel. In order to reduce the void coefficient of the AC design and make its performance less sensitive to variations in

* Corresponding author. Tel.: +1-434-841-0597; fax: +1-510-643-9685.
E-mail address: pmgorman@berkeley.edu

Selection and peer-review under responsibility of the Tokyo Institute of Technology
doi:10.1016/j.egypro.2014.11.856

operating conditions, the RBWR-Th replaces depleted urania with thoria as the primary feed fuel, eliminates the internal blanket, elongates the seed region, and eliminates absorbers from the upper reflector. In order to accommodate newly imposed constraints for coolant dryout and two-phase flow stability, the design underwent a parametric study. Section 2 lists the constraints, section 3 lists the design variables and describes the design process undertaken and the selected configuration, section 4 summarizes the core and fuel-cycle performance metrics of the reference design and compares it with a previous design variant, section 5 demonstrates the performance sensitivity to several uncertain modeling assumptions, and section 6 summarizes results from an assembly-level analysis.

Nomenclature

BOEC	beginning of equilibrium cycle
BOEL	beginning of equilibrium fuel life
BU	burnup
CZP	cold zero power
DR	decay ratio of the core response to DWO perturbations
DWO	two-phase density wave oscillation
EOEC	end of equilibrium cycle
EOEL	end of equilibrium fuel life
FIR	fissile inventory ratio
HFP	hot full power
LHGR	linear heat generation rate
MCPR	minimum critical power ratio
P/D	pitch to diameter ratio
RBWR	reduced moderation BWR
T	cycle length
TRTh	transthorium

2. RBWR-Th core design assumptions and constraints

The RBWR-Th core design is guided by the following mission assumptions and constraints:

1. At equilibrium, charge only natural thoria as the makeup fuel
2. Recycle all transthoria elements
3. Maintain a fissile inventory ratio (FIR) of 1 at equilibrium
4. Fit within an ABWR pressure vessel
5. Provide the full ABWR thermal power
6. Operate for at least 12 month cycles

The core must meet additional physical and operational constraints:

7. Possess negative coefficients of reactivity for fuel temperature, coolant void, and power
8. Maintain criticality
9. Avoid coolant dryout: MCPR $\geqslant$ 1.5 [2]
10. Suppress density wave oscillations: DR < 0.7
11. Have sufficient shutdown margin

Here, MCPR is the minimum critical power ratio, and DR is the decay ratio of the core response to two-phase density wave oscillation (DWO) perturbations [3]. Constraint 10 was selected as a compromise between the GE-Hitachi design constraint of 0.8 and the full power, full flow decay ratio of <0.5 that BWRs typically achieve [3]. More reliable full core stability analysis will be performed in a follow-up study. Constraints 9 and 10 were not considered during the 2011 design effort [4], but are met by the new reference design described in Sections 3 and 4. Failure to meet constraint 11 is discussed in Section 6; it is being successfully addressed in current design studies. No pressure drop constraint was accounted for in this preliminary study.

3. Parametric study of the RBWR-Th core design

The new RBWR-Th parametric study sought to abide by the two recently imposed constraints while maximizing discharge burnup. For this study, a hierarchical approach was taken towards adjusting design variables. Coolant flow rate and fuel residence time were chosen as the two primary design variables because for fixed power (constraint 5), constraint 9 is most sensitive to the former and constraint 8 is most sensitive to the latter. The effects of changes to the seed and blanket region axial lengths, axial isotopic concentration distribution, inlet sub-cooling, fuel pin outer diameter, and fuel pin pitch-to-diameter ratio are multi-faceted, so these variables were selected as secondary design variables.

Each set of secondary design variables uniquely determined the values of the coolant flow-rate and fuel residence time required for meeting constraints 9 and 8 at the beginning and end of the cycle. Upon each choice of primary design variables, a new equilibrium core composition was calculated and the primary design variables were once again updated. A few iterations of primary design variables were required in order to meet constraints 8 and 9. The remaining constraints were satisfied by the adjustment of secondary design variables.

The adjustments of the secondary design variables were guided by a sensitivity study, which estimated the effects of one-at-a-time variable adjustment upon MCPR, DR, and achievable burnup (BU). The qualitative sensitivities are tabulated in Table 1.

Table 1. Effects of primary and secondary design variable changes upon coolant dryout, two-phase stability, and achievable burnup. Here, +'s indicate improvement, –'s indicate deterioration, double symbols indicate large effects, and blanks indicate no or ambiguous effects.

Modification	MCPR	DR	BU
Increase of the coolant flow rate	+	+	–
Increase of the fuel residence time			+
Elongation of the seed	+	–	+
Contraction of the blankets			+
Axial variation of the transthoria loading	+	+	+
Reduction of the inlet sub-cooling		++	
Decrease in fuel pin outer diameter	+	++	
Increase of the fuel pin P/D	+	– –	– –

Elongation of the seed was found to improve MCPR due to a decreased linear heat generation rate (LHGR), to worsen DR due to increased two-phase pressure drop, and to improve BU due to a decreased blanket volume fraction. Contraction of the blanket regions improved DR due to decreased two-phase pressure drop and improved core average BU due to a reduced blanket volume fraction with only a small penalty in breeding [5]. Loading transthoria in axial grades with concentration increasing towards the top of the core improved MCPR by shifting the LHGR upwards, improved DR by reducing the two-phase pressure drop, and improved BU by reducing fluence peaking[5]. Reduction of the inlet sub-cooling improved DR. Reduction of the fuel pin outer diameter improved MCPR by reducing LHGR due to increased number of fuel pins per assembly, but at the cost of worsening DR due to a shortened heat transfer time-constant. An increase of the fuel pin pitch-to-diameter ratio improved MCPR performance by allowing for fuel wetting despite of the increase in the LHGR, but significantly penalized BU.

Based upon this sensitivity study, several design variable changes were made to the 2011 design [4] in order to improve the MCPR and DR (constraints 9 and 10): the coolant flow rate and fuel residence time were increased by 30%; the seed region was elongated by 170%; the total blanket length was contracted by a third; and transthoria was loaded into the seed at three concentrations – 75% of the average for the lower third, the average for the middle third, and 125% of the average for the upper third. These changes, when combined, guaranteed that constraint 9 was met, reduced the DR, and provided a minimal penalty on the discharge burnup. Additionally, the inlet subcooling was reduced by 4.06°C in order to match the subcooling temperature used in the Hitachi design [1]. The fuel pin outer diameter and pitch and assembly thermal power remained unchanged. Table 2 provides the resulting main design specifications.

Table 2. Main design specifications of the 2013 reference RBWR-Th core design. Here, LB/S/UB refers to the lower blanket, seed, and upper blanket axial regions, TRTh denotes transthoria, and L/M/U are the lower, middle, and upper axial third of the seed region.

Design variable	Units	Value
Thermal power	MW	3926
Coolant flow rate	kg/s	8795
Fuel residence time	EFPD	2300
Fuel pin length (LB/S/UB)	cm	40/300/40
Seed TRTh loading (L/M/U)	$^{a}/_{o}$ of average	75/100/125
Fuel pin OD/pitch	cm	1.005/1.135
Coolant inlet temperature	°C	282.56
Coolant inlet pressure	MPa	7.25

4. Performance of the 2013 reference RBWR-Th core design

The MocDown equilibrium search tool [6] was used to arrive at the 2013 reference RBWR-Th core design based on unit cell analysis. The full-core k_{eff} are derived from the unit-cell results assuming a five batch fuel management and equal power batches using the harmonic mean:

$$k_{eff}(t) = 5 * \left[\frac{1}{k_{\infty(t)}} + \frac{1}{k_{\infty(t+T/5)}} + \frac{1}{k_{\infty(t+2T/5)}} + \frac{1}{k_{\infty(t+3T/5)}} + \frac{1}{k_{\infty(t+4T/5)}} \right]^{-1} - 0.025 \qquad (1)$$

in which T is the cycle length. The full-core radial leakage probability, assumed to be 2.5%, was subtracted from the harmonic mean; it was assumed to be invariant with fuel temperature and coolant void perturbations. The axial leakage is accounted for in the unit cell analysis. Instantaneous reactivity coefficients are calculated similarly:

$$RC = \frac{\dfrac{1}{k_{\text{nominal}}} - \dfrac{1}{k_{\text{perturbed}}}}{\Delta\text{perturbation}} \qquad (2)$$

and full-core reactivity coefficients are calculated using the arithmetic mean of the instantaneous reactivity coefficients for each batch.

Using MCNP6.1 [7] for neutron transport with the ENDF/B-VII.0 cross section library and ORIGEN2.2 [8] for transmutation, 55 axial fuel zones were depleted – 10 lower blanket, 30 seed, and 15 upper blanket – in 14 constant-power depletion steps. Online coupling of a single-channel heat balance and void fraction correlation ensured self-consistent neutronics (power distribution) and thermal/hydraulics (coolant density distribution) solutions such that the maximum water density difference between transport iterations was within 5%. Loaded fuel was assumed to be at 90% of its nominal density. Fuel was recycled through the system over 50 times before reaching an asymptotic equilibrium (defined when the batch-averaged k_{eff} was within 150 pcm of the previous cycle). The void fraction axial distribution was estimated using an MIT-modified LPG correlation [2]. An MIT-modified CISE-4 correlation was used to estimate the critical power ratio, while assuming a 25% inter-assembly power peaking and a 5% coolant flow-rate reduction [2]. The density wave oscillation decay ratio was estimated using the STAB frequency domain stability code [9]. As shown in section 5, the system is very sensitive to thermal hydraulic conditions, the uncertainties of which are large but not readily quantifiable. The statistical uncertainties from MCNP6.1 are not presented as they are small as compared to the thermal-hydraulic uncertainties.

Table 3 summarizes the core and fuel cycle performance metrics for the 2013 reference design and compares them with those of the 2011 design [4]. The 2013 design offers a smaller core average discharge burnup. At beginning of equilibrium life (BOEL) thorium makes 88.4 $^{w}/_{o}$ and ^{233}U makes 5.1 $^{w}/_{o}$ of the seed HM; the latter is 43.6 $^{w}/_{o}$ of the transthorium inventory. Overall, 6.5 $^{w}/_{o}$ of the seed HM – 56 $^{w}/_{o}$ of all transthorium – is fissile. Compared to the 2011 reference, the 2013 design features an elongated and flattened LHGR distribution, as shown in Fig. 1. Whereas the 2011 LHGR peaks at 280 W/cm in the lower seed at BOEL, the 2013 LHGR peaks only at 100 W/cm in the upper seed at EOEL. Also seen is the larger amount of breeding within the blankets of the 2011 design due to a shorter seed and, therefore, a higher probability of leakage from the seed into the blanket. Fig. 2 shows the axial distributions of ^{232}Th and ^{233}U over a cycle. The graded transthorium feed concentrations are clearly seen. It is evident that the transmutation of ^{232}Th to ^{233}U is higher in the seed than in the blanket, but the consumption of ^{233}U in the seed is sufficiently higher that more ^{233}U accumulates in the blankets than in the seed.

Table 3. Core and fuel cycle performance metrics of the 2011 and 2013 reference RBWR-Th core designs. Here, FTCR and VCR are the fuel temperature and coolant void coefficients of reactivity, and B/E denote conditions at the BOEC and EOEC states. A 34.5% thermodynamic efficiency is assumed for both variants.

Performance metric	Units	2011	2013
Fissile inventory ratio	-	1	1
Cycle length	EFPD	356	460
# of batches	#	5	5
Average discharge burnup	GWd/t	32	25
Minimum CPR	-	1.1	1.5
DWO decay ratio	-	1.23	1.08
Average power density	MW_{th}/m^3	70	42
Maximum LHGR	W_{th}/cm	300	100
Average specific power	MW_e/t	6	4
Transthorium abundance in seed	$^{w}/_{o}$	12.7	11.6
Transthorium specific loading	t/GW_e	20.5	30.9
Heavy-metal reprocessing rate	t/GW_e·y	33	42
Transthorium discharge rate	t/GW_e·y	4.2	4.9
FTCR (B/E)	pcm/K	-4.2/-4.2	-4.9/-4.8
VCR (B/E)	pcm/%	-87/-63	-145/-117
Cycle reactivity swing	%Δk	1.9	0.85
Total void collapse reactivity worth (B/E)	%Δk	19/17	22/20
Outlet void fraction	%	82	75

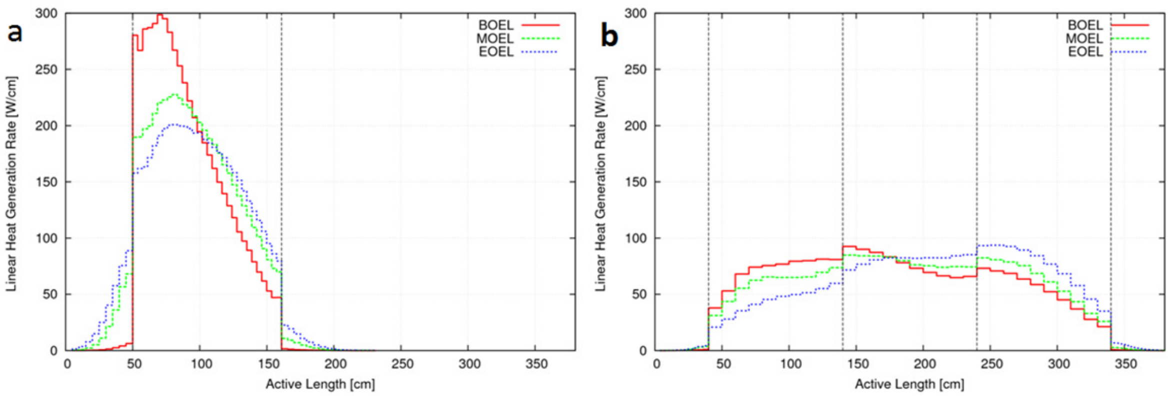

Fig. 1. LHGR of the (a) 2011 and (b) 2013 reference RBWR-Th core designs. The elongated active region and graded transthoria concentration of the 2013 variant significantly lowers its LHGR and flattens its distribution.

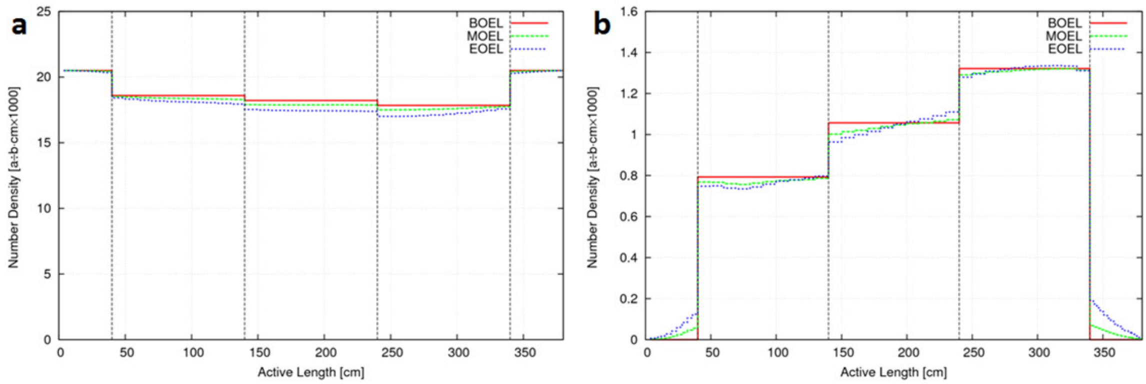

Fig. 2. Axial concentration of (left) ^{232}Th and (right) ^{233}U along a cycle of the 2013 design. Transthoria is charged in graded enrichments within the seed.

5. Sensitivity of performance to modeling assumptions

RBWR-Th performance is highly sensitive to the void fraction, critical power, and, to a lesser extent, core radial leakage probability. The first two are estimated by correlations with large experimental uncertainties [2] and the third requires a full-core analysis. The impact of these uncertain modeling assumptions upon performance is quantified by relaxing the assumptions in turn and re-optimizing the design. These results are summarized in Table 4.

The MIT-modified LPG correlation [2] was assumed to offer a best-estimate of the RBWR-Th coolant void fraction which is conservatively lower than that predicted by the RELAP correlation [2], used by Hitachi to model the RBWR-AC. Upon switching to the RELAP correlation [2], the estimated coolant void fraction increases, system slowing-down power decreases, flux spectra harden, fissile breeding improves, equilibrium fissile content increases, and longer fuel residence times can be achieved [10]. The result is an increase in the achievable burnup from 25 to 38 GWd/t. Additionally, the higher void fractions and increased fissile content make the void coefficients of reactivity less negative, so the DWO decay ratio drops from 1.08 to 1.00.

The MIT-modified CISE-4 (MCISE) correlation [2] was assumed to offer a best-estimate of the RBWR-Th critical power and recommends a conservative limit of 1.5. Hitachi uses its own modified CISE-4 correlation (H-CISE) and a 1.3 limit which permits less wetting of the fuel before dryout. Upon switching to the Hitachi-used correlation and limit, a reduced coolant flow and shortened active fuel length can be accommodated, which, when combined, improves both burnup and stability. The former does so by increasing coolant void fraction and the latter does so by reducing the heavy metal loading and reducing the two-phase pressure drop. This switch, in addition to the usage of the RELAP void fraction correlation, more than doubles the achievable burnup from 25 to 61 GWd/t and drops the DWO decay ratio from 1.08 to 0.48.

The attainable burnup was estimated assuming a 2.5% core radial leakage probability. Recent studies indicate it to be 2.2%. Changing the core radial leakage probability from 2.5% to 2.2% results in an achievable burnup increase of roughly 16%.

Table 4. Summary of performance sensitivity to modeling assumptions. LPG and RELAP are drift-flux correlations for void fraction and M-CISE and H-CISE are correlations for critical power.

Modeling change	Metric	Impact
LPG to RELAP	BU	25 to 38 GWd/t
	VCR	less negative
	DR	1.08 to 1.00
LPG to RELAP & M-CISE to H-CISE	BU	25 to 61 GWd/t
	DR	1.08 to 0.48

2.2% to 2.5% leakage	BU	25 to 29 GWd/t

6. Fuel assembly physics study

A fuel assembly unit cell analysis was performed to estimate the control element reactivity worth, the within assembly pin-wise power distribution and power peaking, and the effects of the flow bypass region, assembly can, and control blade followers on selected performance characteristics. A cross section cut of the assembly unit cell model used for this analysis is depicted in Fig. 3. This unit cell was simulated with Serpent using the ENDF/B-VII.0 cross section library. The hot full-power (HFP) conditions are the same as of the pin model (Table 2). Cold zero-power (CZP) conditions used 300K water density in the entire assembly and 300K cross sections.

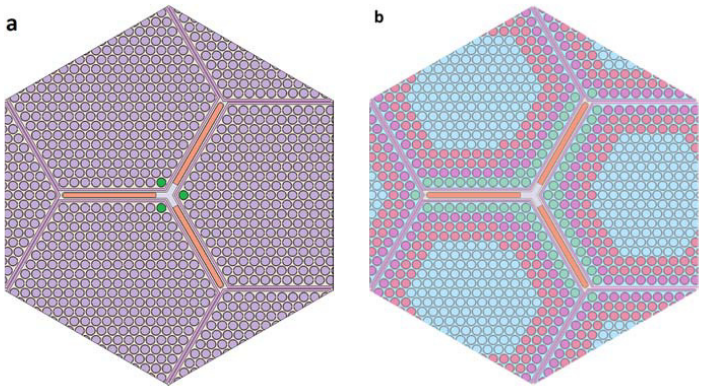

Fig. 3. RBWR-Th multi-assembly unit cell (a) with uniform enrichment and (b) with the final enrichment scheme. The corner pin is denoted in green in (a).

It was found that the assembly can slightly increase parasitic absorption and the flow bypass region and control blade followers greatly increase moderating power at the assembly periphery. The enhanced local moderation was found to cause a power peaking of 1.4 in the corner pin at BOEC. Upon loading transthoria in four radial grades – increasing fissile content at the interior of the assembly and reducing it at the edges – the power peaking was reduced to 1.1 at BOEL and 1.2 at EOEL. Fig. 3 (right) and Table 4 define the enrichment scheme, and Fig. 4 shows the BOEL pin power peaking.

Table 5. Summary of different radial enrichment groups. The color refers to the color in Fig. 3.

	Color	# Pins:	Transthorium Concentration
Group 1	Blue	113	113.5%
Group 2	Red	83	100%
Group 3	Purple	55	85%
Group 4	Green	20	65%

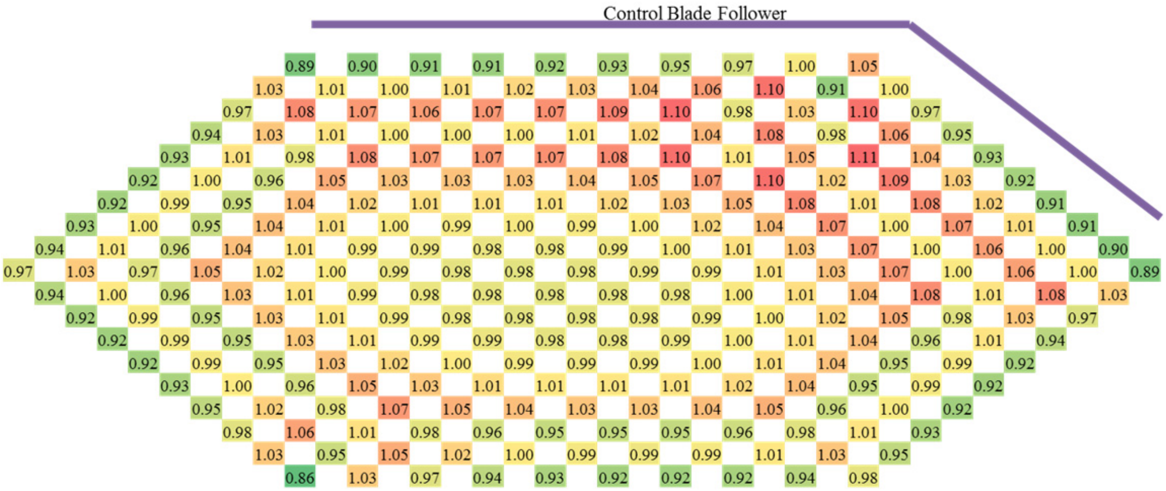

Fig. 4. BOEL pin power distribution. The numbers for each position values are the pin power divided by the average pin power.

The reactivity worth of the RBWR-AC [1] like B_4C control blades when fully inserted into the RBWR-Th 2013 assembly unit cell was found to be ~10% – not sufficient to counteract the reactivity gain of about 13% going from HFP to CZP states. The actual reactivity deficiency of the control rods is larger since the reactivity gain due to the decay of ^{233}Pa to ^{233}U and ^{135}Xe to ^{135}Cs was not accounted for and none of the control rods was assumed stuck in the withdrawn position.

The control worth deficit could be addressed by increasing the ratio of control to fuel elements (by either reducing the number of fuel pins per assembly or increasing the number of control blades per assembly). However, such a design change would increase the volume of assembly bypass and penalize achievable burnup through spectrum softening and enhanced parasitic neutron capture. The feasibility of increasing the reactivity worth of the control rods by modifying the design and composition of the control blades was investigated. The results are summarized in Table 6; it is clear that no realistic control blade design would be able to shut down the core.

Table 6. Summary of control element design study. Only the black control element was able to meet the non-conservative 13%Δk shutdown requirement.

Variations of Hitachi control element	Shutdown worth [%Δk]
Original (SS sheath; B4C absorber)	-9
W sheath	-10
Hf sheath	-11
W sheath + 2× B4C absorber	-11
W sheath + AgInCd absorber	-5.7
Gd sheath + Gd absorber	-5.8
Hf sheath + Hf absorber	-6.5
Black sheath + black absorber	-32

The approach presently being pursued for attaining desirable shutdown margin is to mix depleted urania with the thoria feed fuel. The plutonium and higher actinides bred into the fuel make the VCR less negative and thus reduce the HFP-to-CZP reactivity gain than need be compensated by the control rods. The reduced magnitude of the VCR would also improve two-phase flow stability.

7. Conclusions

The RBWR-Th core design was improved to accommodate coolant dryout and two-phase flow stability constraints. By elongating the seed and flattening the LHGR profile, shortening the blankets, axially varying the transthorium elements seed loading, and reducing the inlet subcooling, the constraints were met with only modest penalties on the fuel discharge burnup. The core performance is highly sensitive to modeling assumptions. Using the MIT recommended correlations and assumptions the attainable core average burnup is 25 GWd/t. However, using assumptions and correlations Hitachi used for the design of their RBWR-AC, the RBWR-Th average discharge burnup is 61 GWd/t versus 45 GWd/t of the depleted uranium fueled RBWR-AC. All coefficients of reactivity are negative, but the void coefficient of reactivity is too negative to allow for safe shutdown at cold zero-power conditions. Moreover, the present study did not account for a constraint on the pressure drop. Ongoing studies are addressing the shutdown margin and coolant pressure drop constraints.

Acknowledgments

This research was performed using funding received from the U.S. Department of Energy Office of Nuclear Energy's Nuclear Energy University Programs. This research is also partially supported by the U.S. Department of Energy National Nuclear Security Administration under Award Number DE-NA0000979.

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